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Title: The Design and Analysis of Protocols for Communication Networks

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The design and analysis of Protocols for Communication Networks

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Los Alamos National Laboratory

NNSA

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Talk Based on the following papers

- Maneuvrable Relays to Improve Energy Efficiency in Sensor Networks, S. Eidenbenz, L. Kroc, J.P. Smith, PERCOM 2005
- Parametric Probabilistic Sensor Network Routing, C. Barrett, S. Eidenbenz, L. Kroc, M. Marathe and J. Smith, WSNA 2003
- Equilibria in Topology control games for ad hoc networks, S. Eidenbenz, V.S. Anil Kumar, S. Zust, DIALM 2003
- Ad hoc-VCG: a truthful and cost-efficient routing protocol for mobile ad hoc networks with selfish agents, L. Anderegg and S. Eidenbenz, MOBICOM 2003
- G. Istrate. The phase transition in random Horn satisfiability and its algorithmic implications, Random Structures and Algorithms, 4 (2002), pp. 483-506.
- G. Istrate. On the satisfiability of random k-Horn formulas, in Graphs, Morphisms and Statistical Physics (edited by J. Nesetril and P. Winkler), pp. 113, AMS-DIMACS series in Discrete Mathematics and Theoretical Computer Science, (2004).
- G. Istrate. Computational Complexity and Phase transitions, in Proceedings of the 15th I.E.E.E. Conference on Computational Complexity, 2000.
- End-to-end packet scheduling in ad hoc networks, V.S. Anil Kumar, M. Marathe, S. Parthasarathy and A. Srinivasan, *SODA, 2004*.
- The distance-2 matching problem and its relationship to the MAC-layer capacity of ad hoc networks, H. Balakrishnan, C. Barrett, V. S. Anil Kumar, M. Marathe, S. Thite, *Special Issue of IEEE Journal on Selected Areas in Communication*
- Algorithmic aspects of capacity in wireless networks, V.S. Anil Kumar, M. Marathe, S. Parthasarathy and A. Srinivasan, ACM SIGMETRICS 2005
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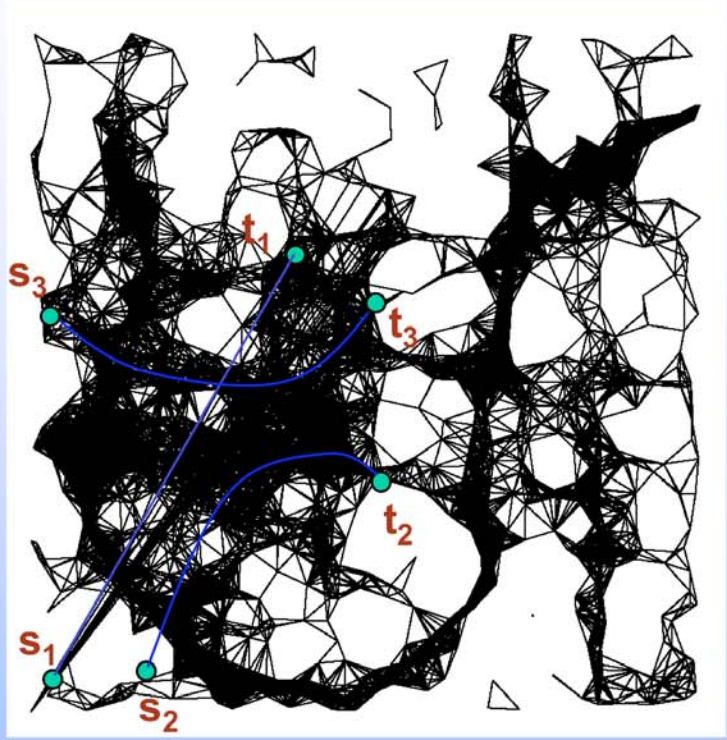
Mobile, Dynamic Networks

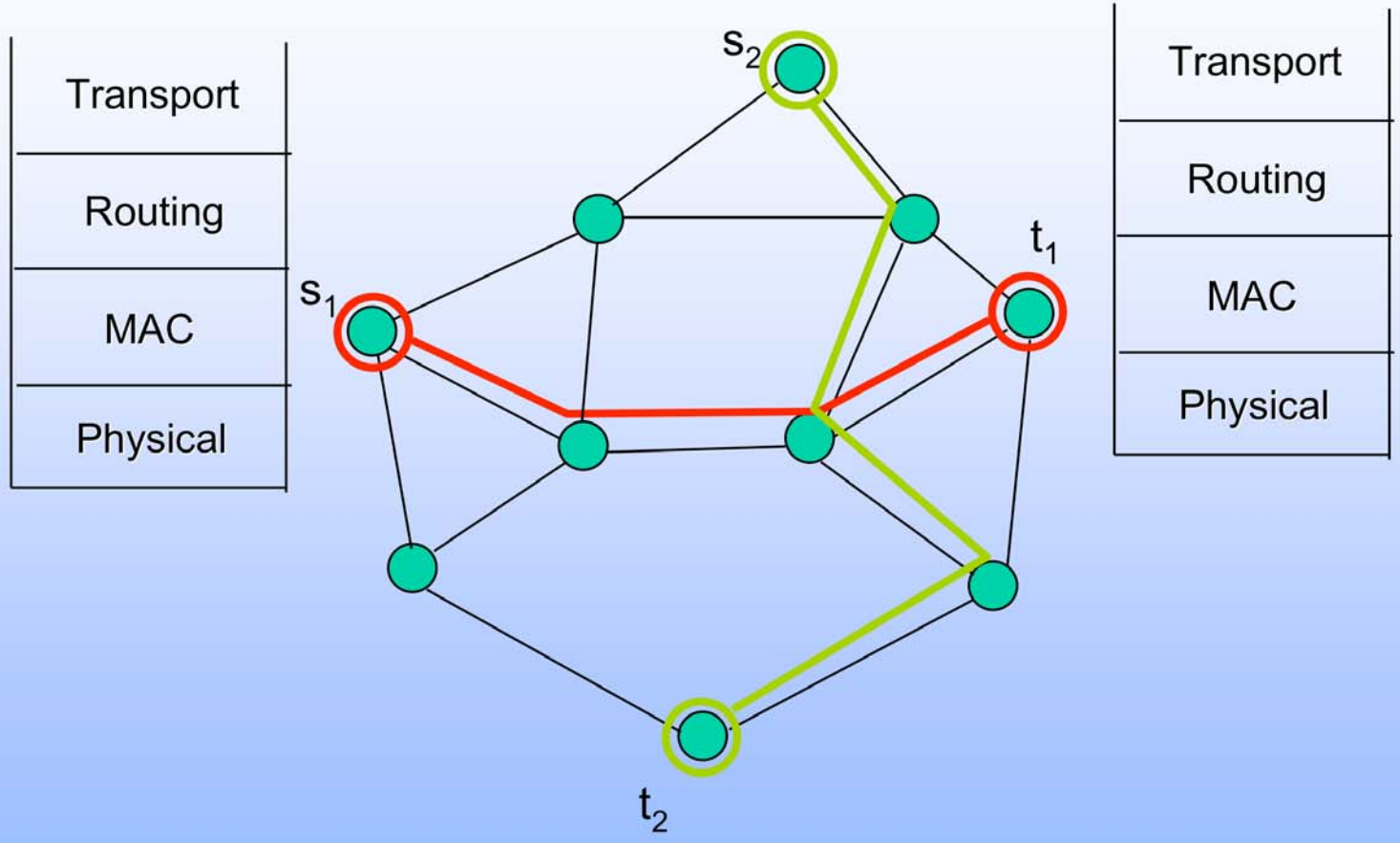
Dynamic Ad-hoc Networks

Communicating on a network



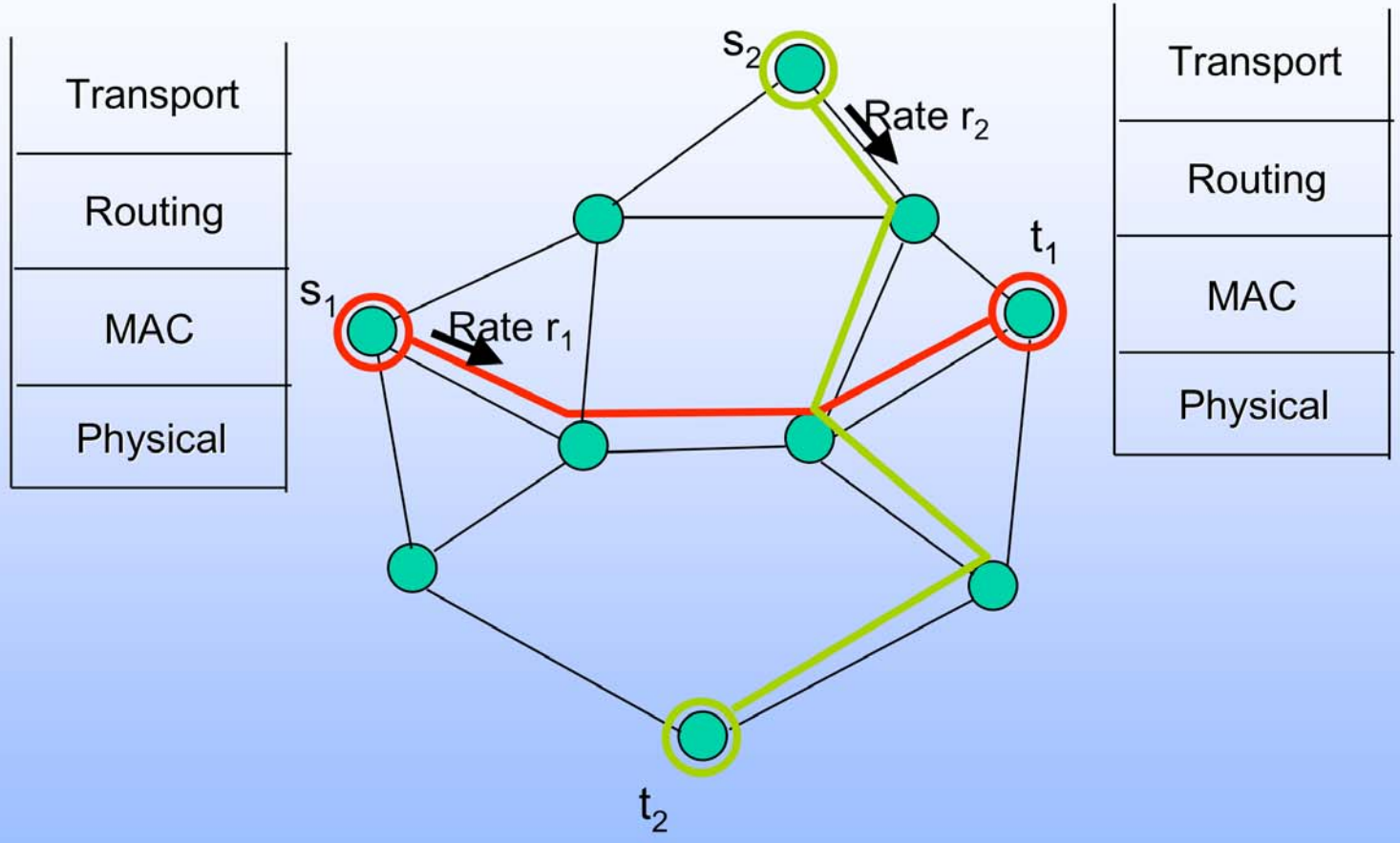
- What is the maximum data transmission rate (capacity)?
- Protocols for communications

The OSI Protocol Stack



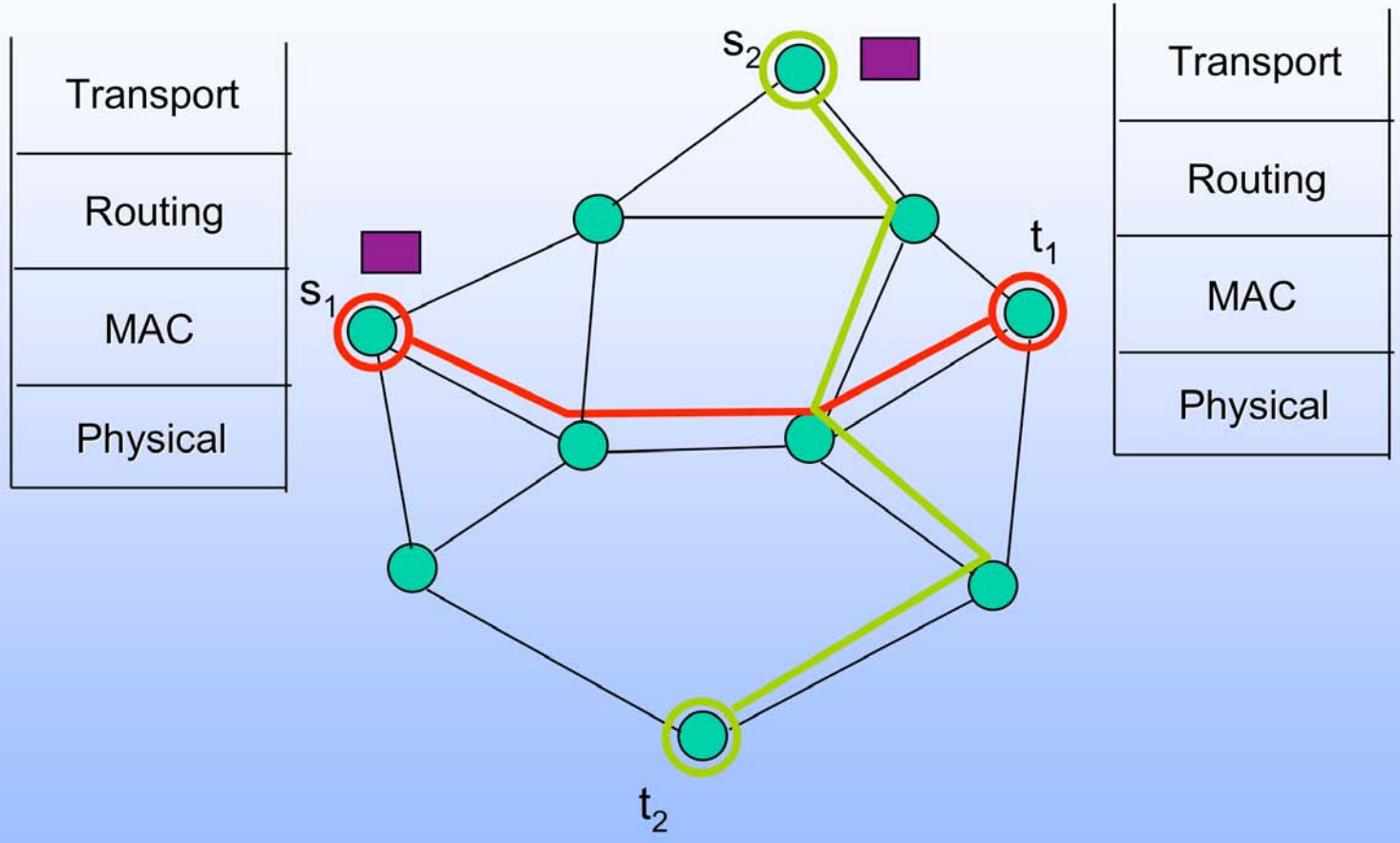
Choose routes (Routing layer)

The OSI Protocol Stack



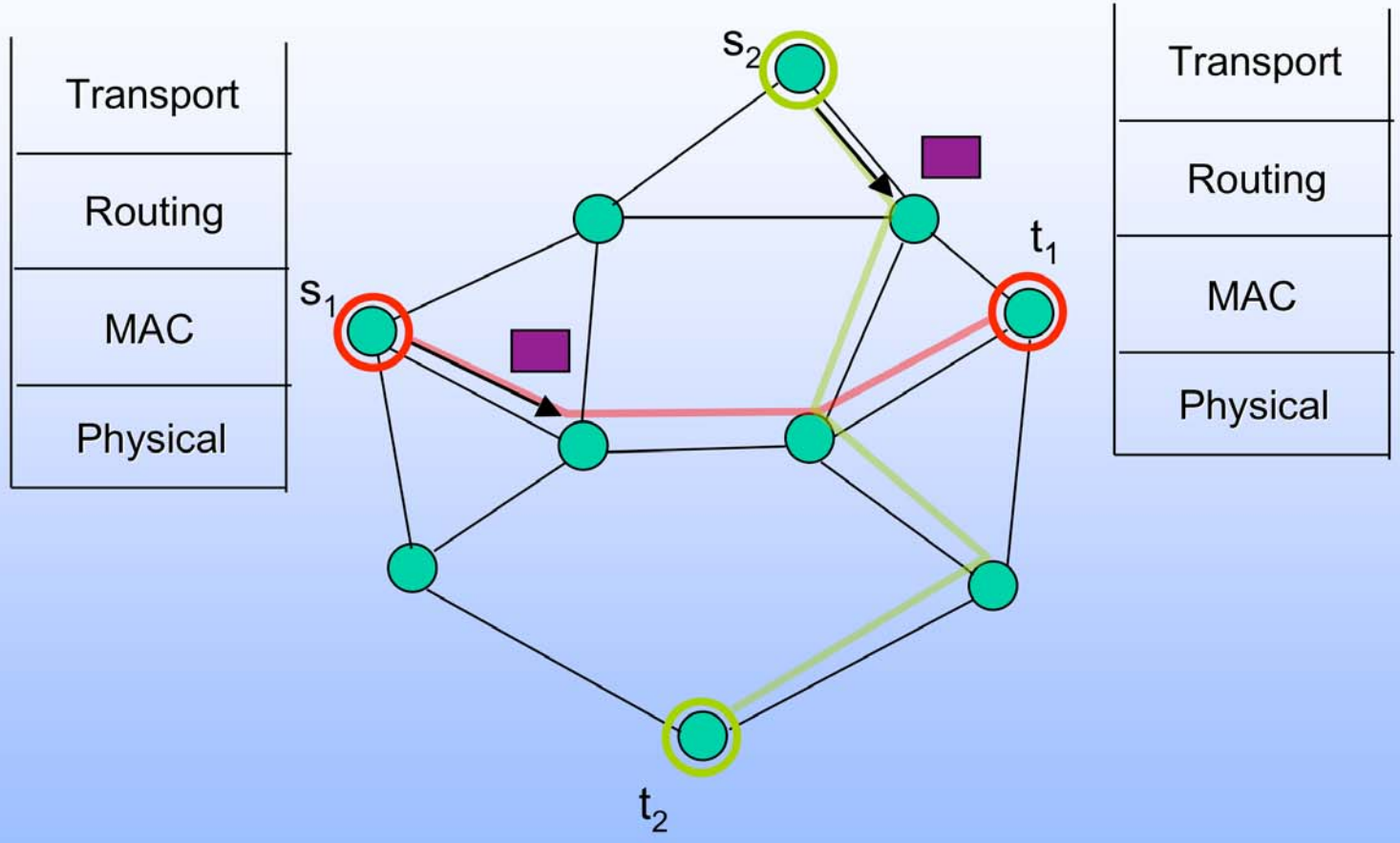
Choose rates (Transport layer)

The OSI Protocol Stack



Transmit one link at a time (MAC layer)

The OSI Protocol Stack



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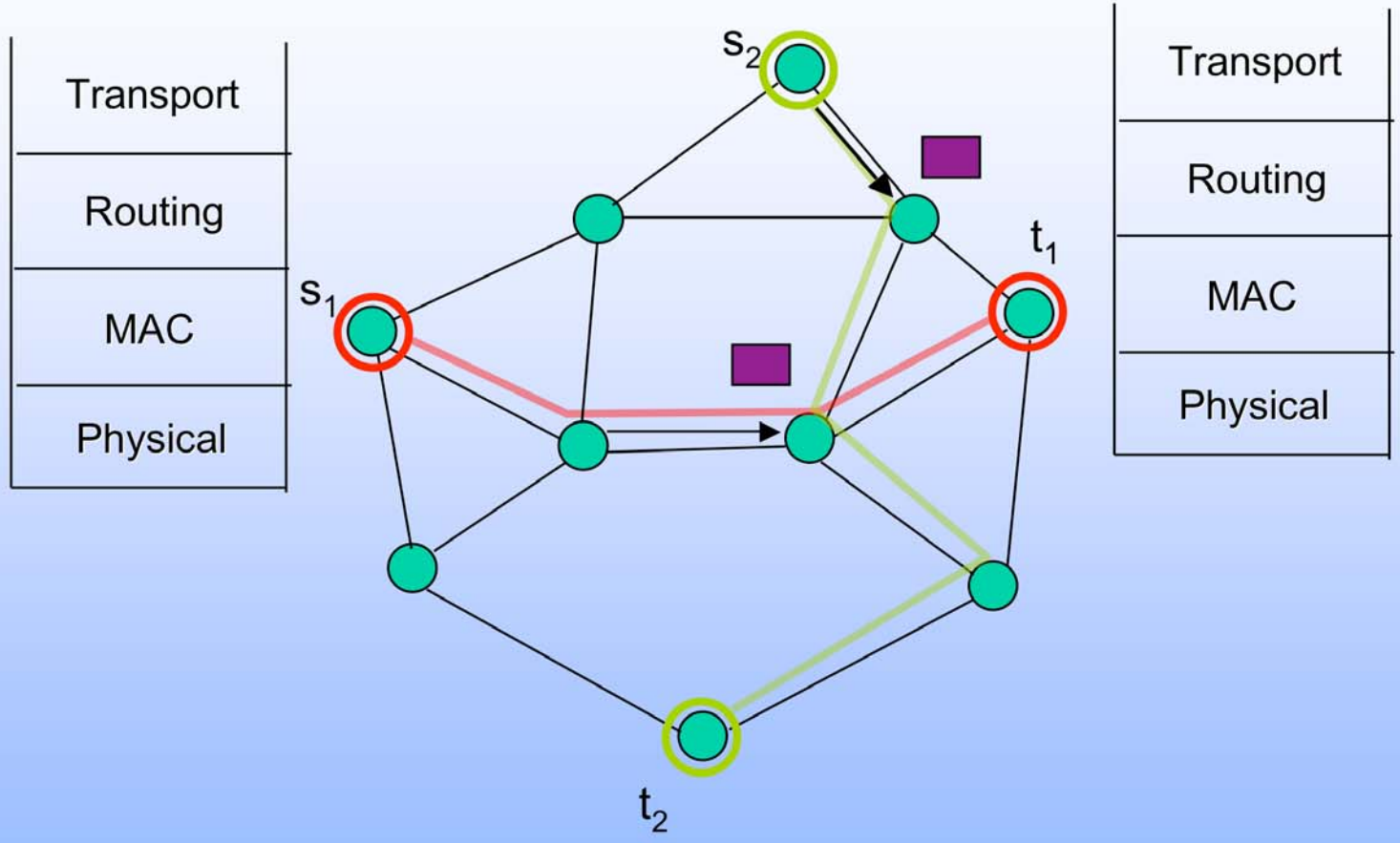

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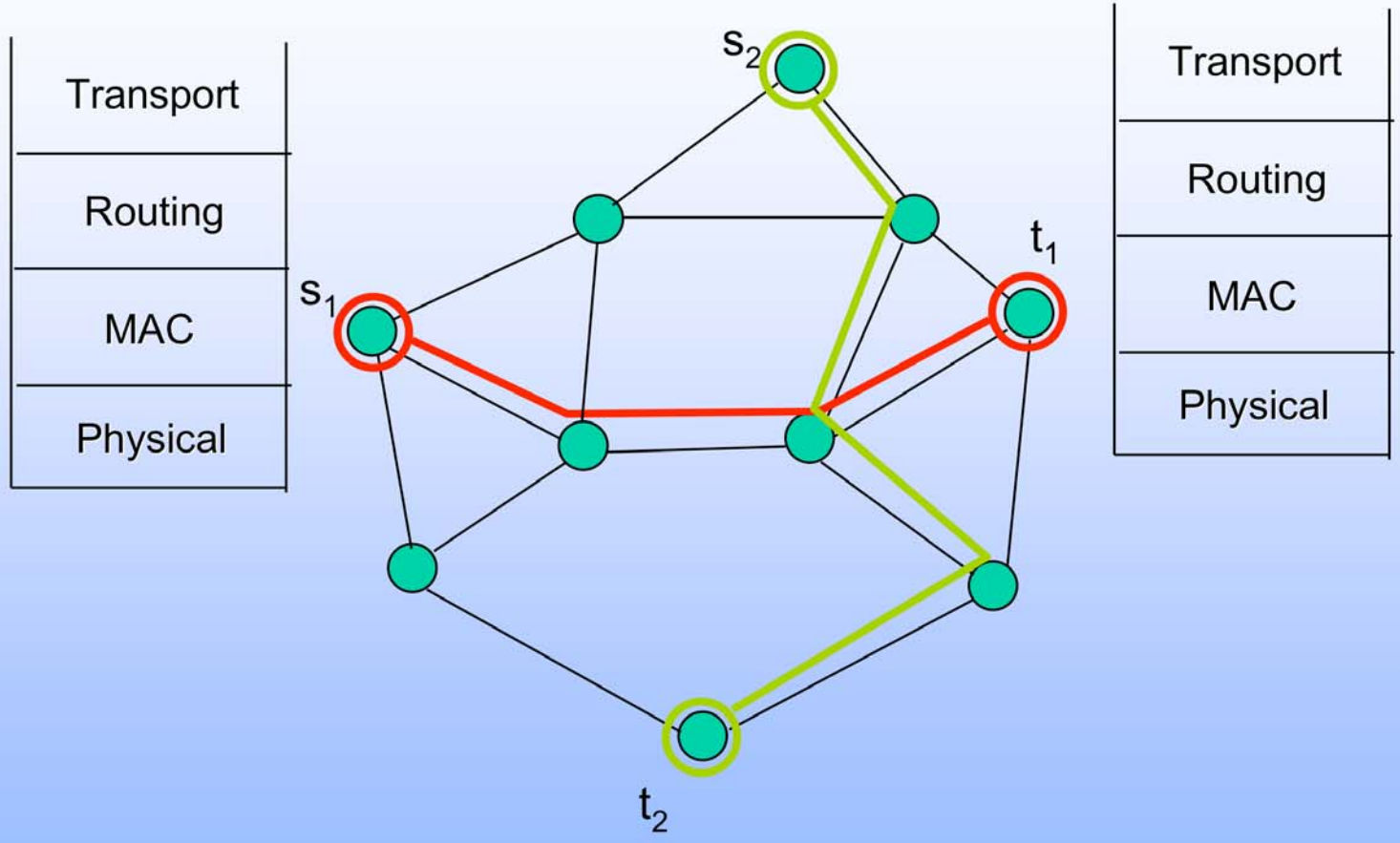
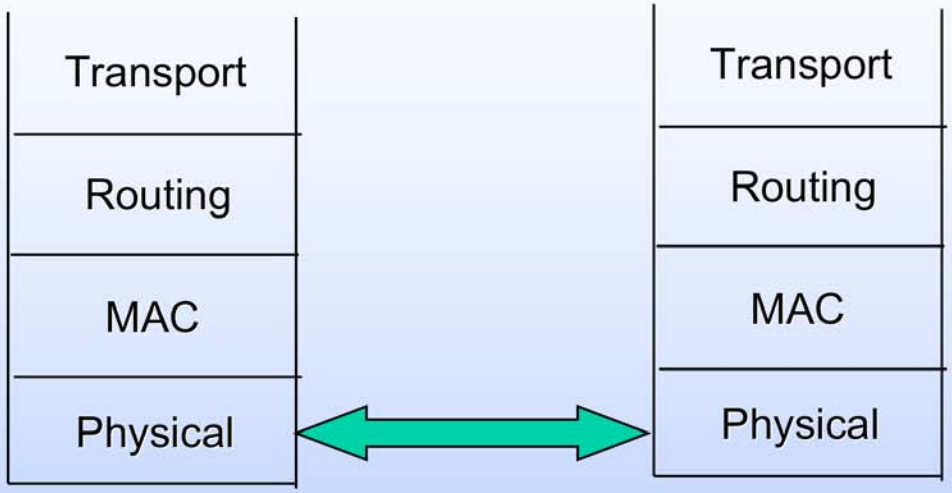


Actual transmission on each link (Physical layer)

This talk…

- Need for Unified Protocols:
  - cross layer interaction and efficient simulations
- Combinatorial formulations:
  - Interference Models for Ad-Hoc Networks: distance-2 matching
  - Unified protocol for MAC+Routing+Transport
- Summary of Results of protocol research
- Conclusions and future work

Protocol Interaction



OSI Protocol Stack

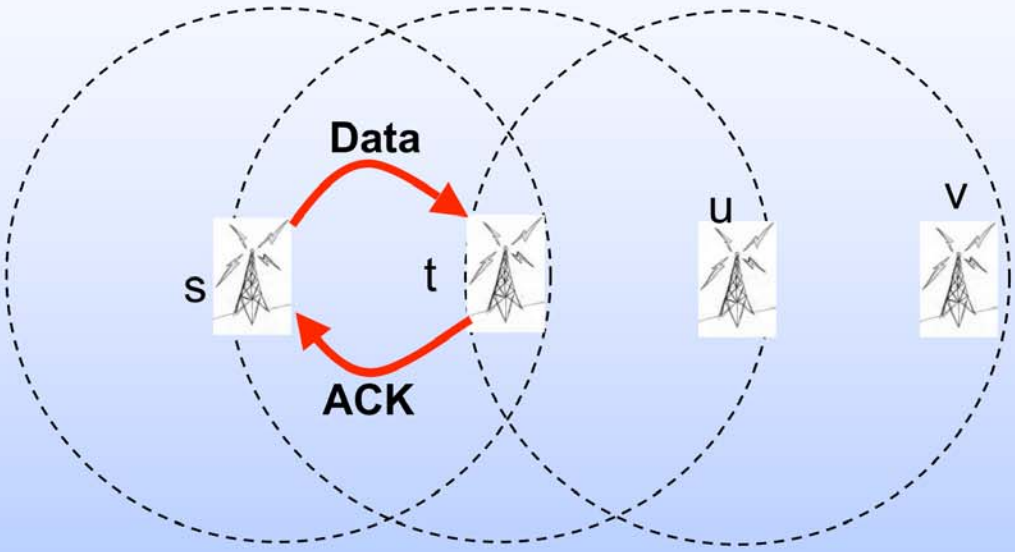
- Significant and quantifiable interaction between MAC and Routing layers
  - Congestion might make shortest path routing inefficient
- Plugging in optimal protocols for each layer might not be optimal overall[1]

[1]Characterizing the Interaction between Routing and MAC protocols in Ad-hoc Networks, C. Barrett, M. Drozda, A. Marathe and M. Marathe, in MobiHoc 2002, WCNC 2003

Efficient Simulations

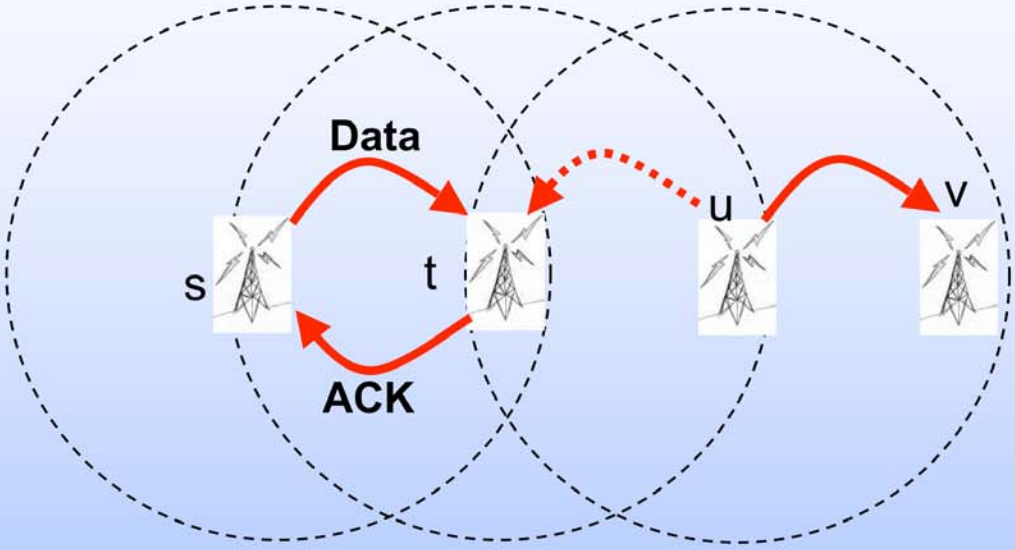
- Current network simulators do not scale:
  - ns/OPNET ~ 100 nodes, GloMoSim/qualnet ~ 1000 nodes
  - Very detailed representation for protocols at individual layers
  - Do not produce the same results
- Only solution: efficient, approximate representation of the whole protocol stack
- (Behavioral) Validation of an approximate protocol representation

MAC Layer Constraint in Ad-hoc Networks



- Radio broadcast: all nodes within broadcast range can hear
- 802.11 model: two way communication

MAC Layer Constraint in Ad-hoc Networks



- Radio broadcast: all nodes within broadcast range can hear
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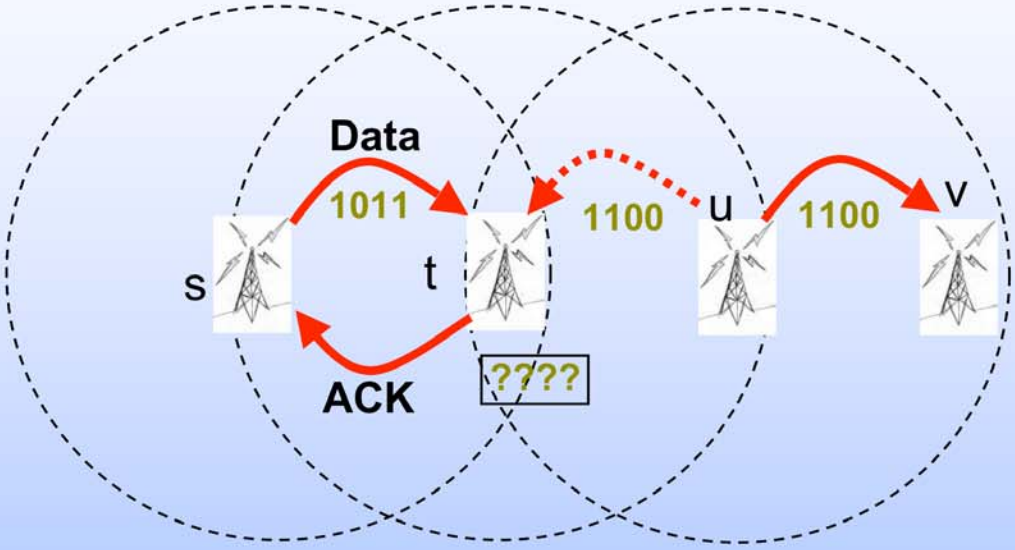
MAC Layer Constraint in Ad-hoc Networks

Assumption: Message is completely lost if a collision occurs



MAC Layer Constraint in Ad-hoc Networks

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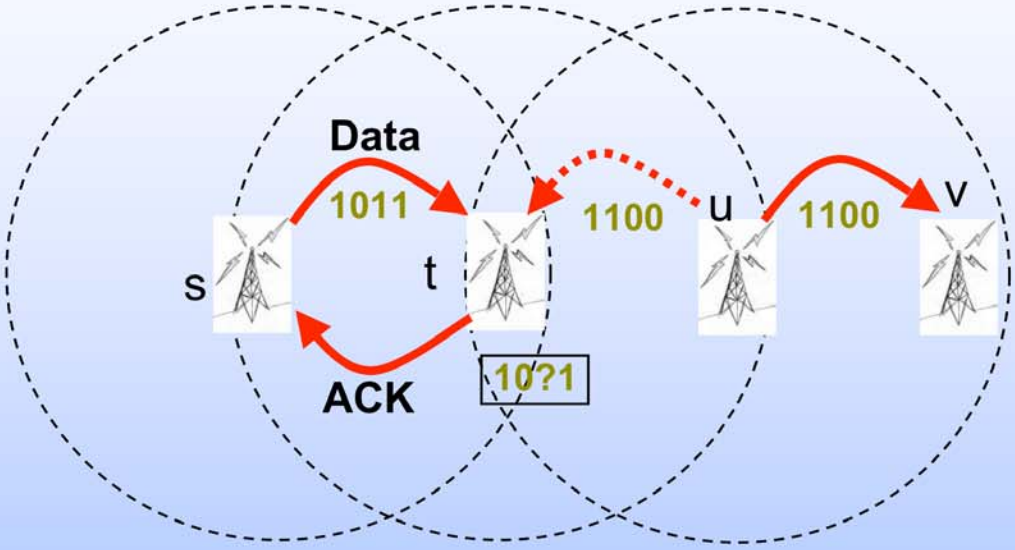
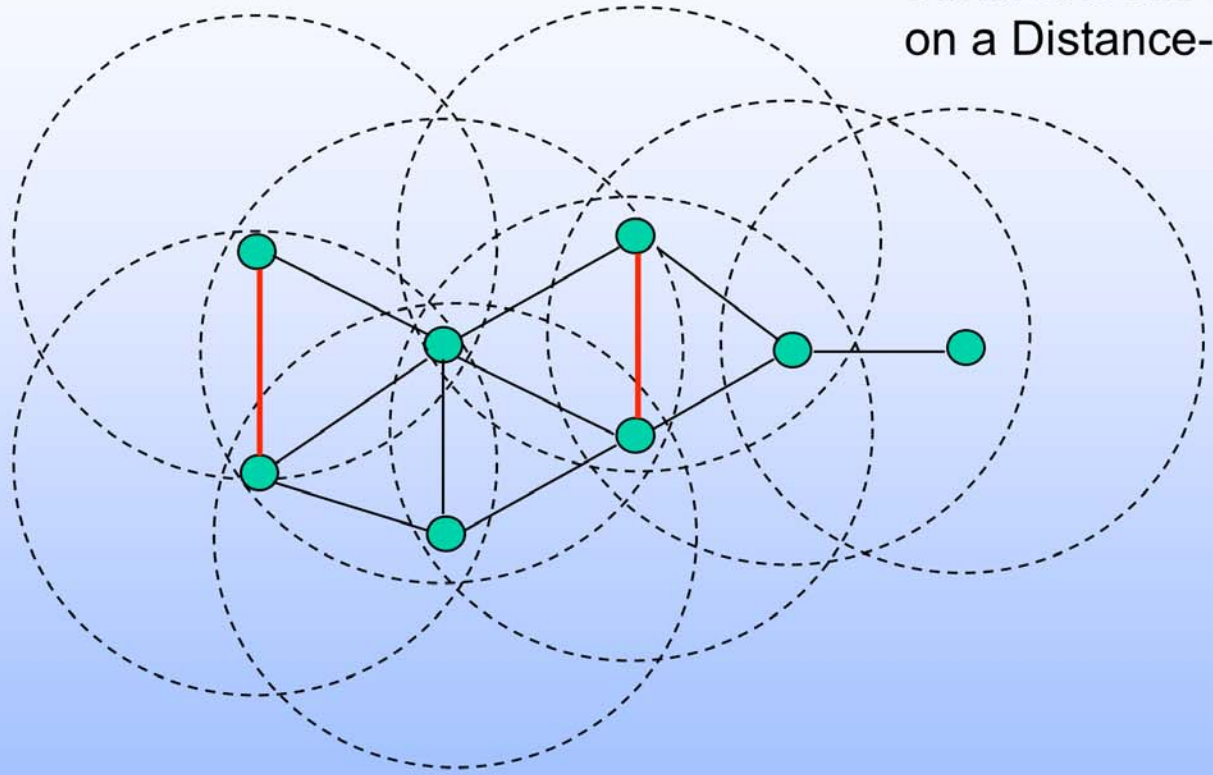


In Reality: Message received with errors
⇒ coding and error correction

Distance-2 Matching

Simultaneous transmission possible on a Distance-2 matching



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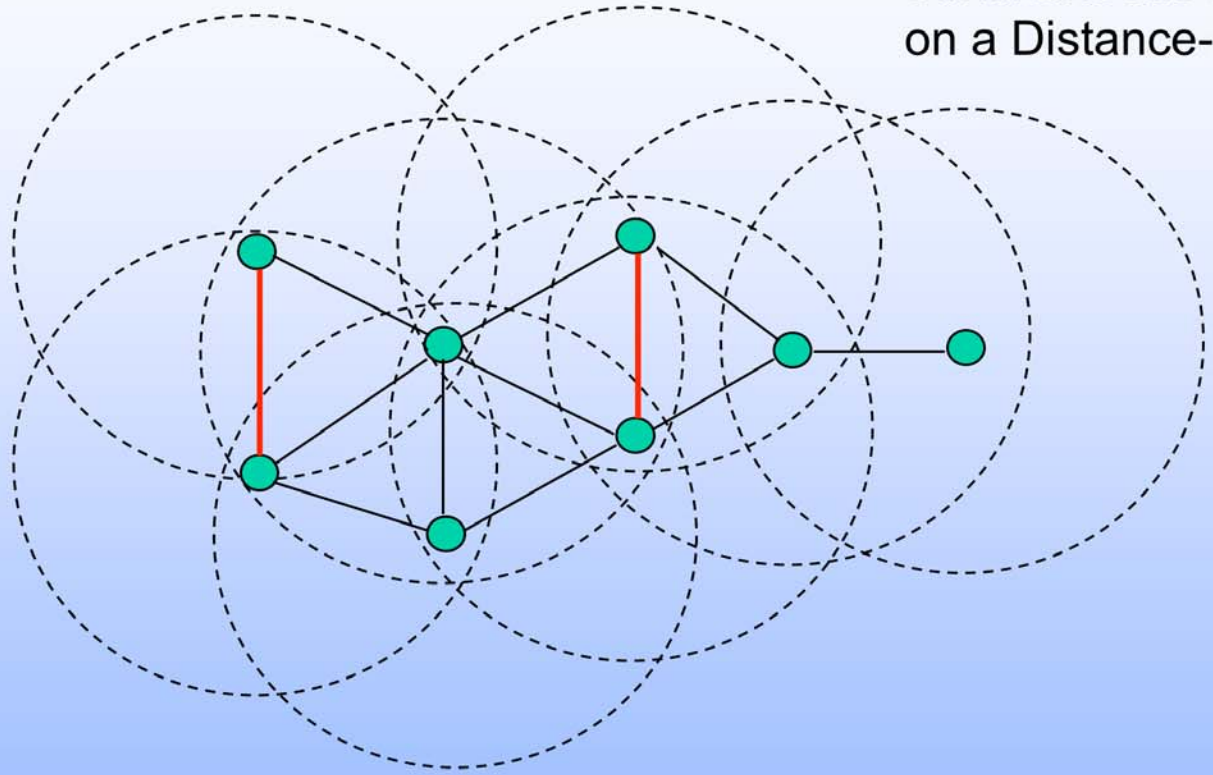

MAC Scheduling problem: choose a Distance-2 matching each time

Distance-2 Matching

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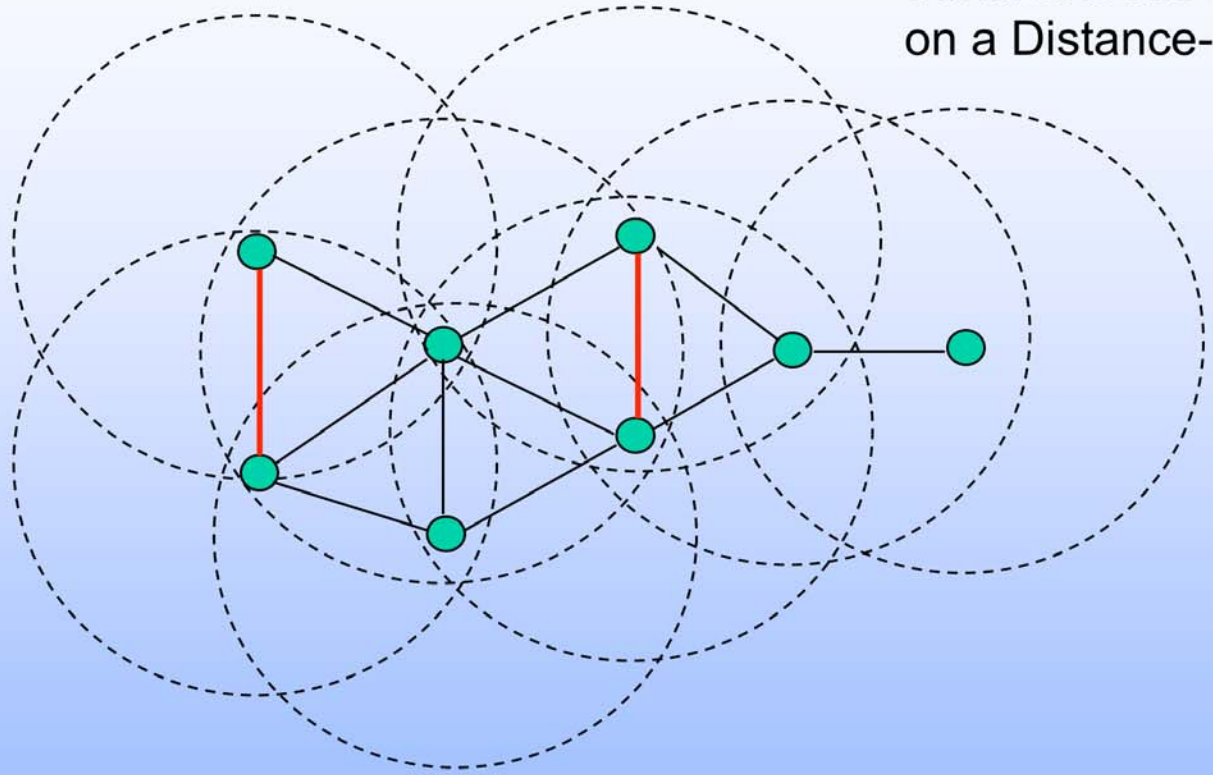
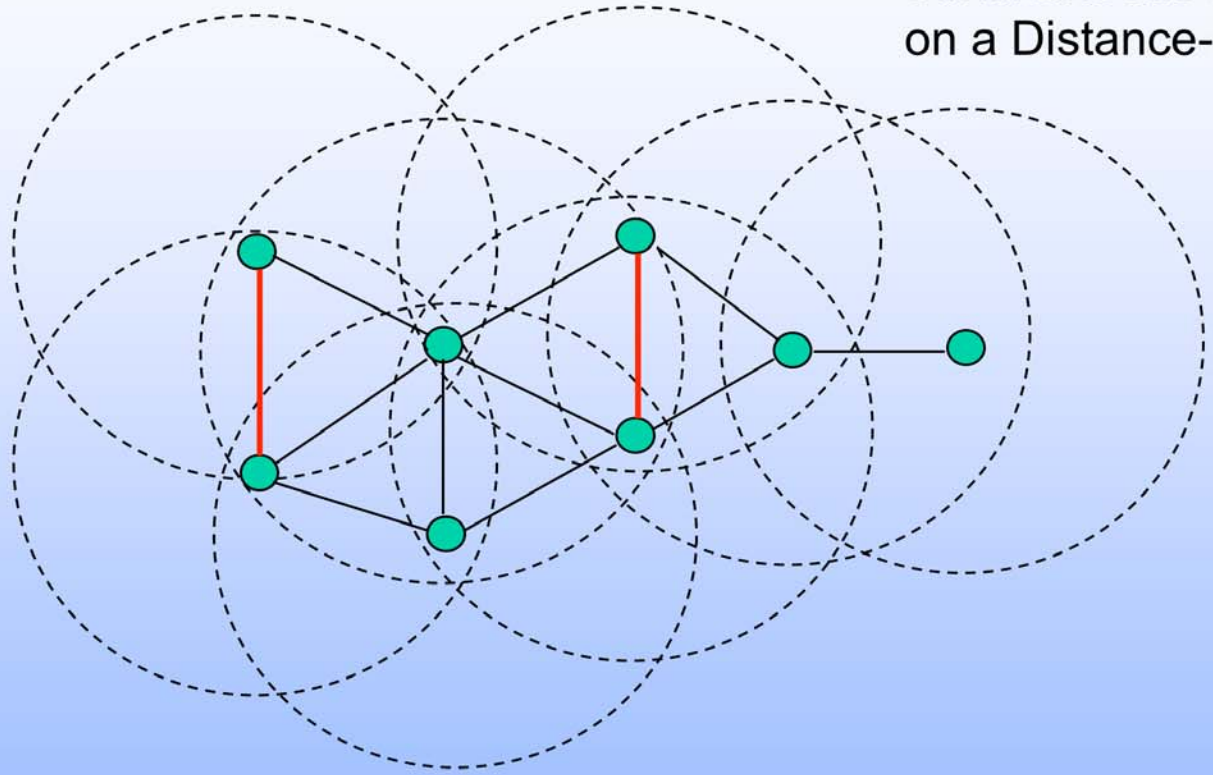


MAC Scheduling problem: choose a Distance-2 matching each time

⇒ Given a set of edges on which to transmit, partition them into a set of Distance-2 matchings

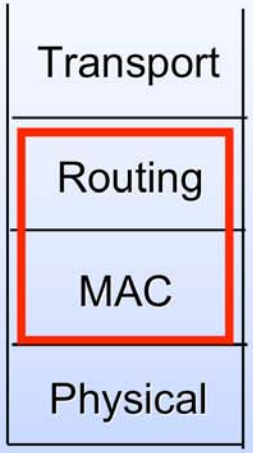
Distance-2 Matching

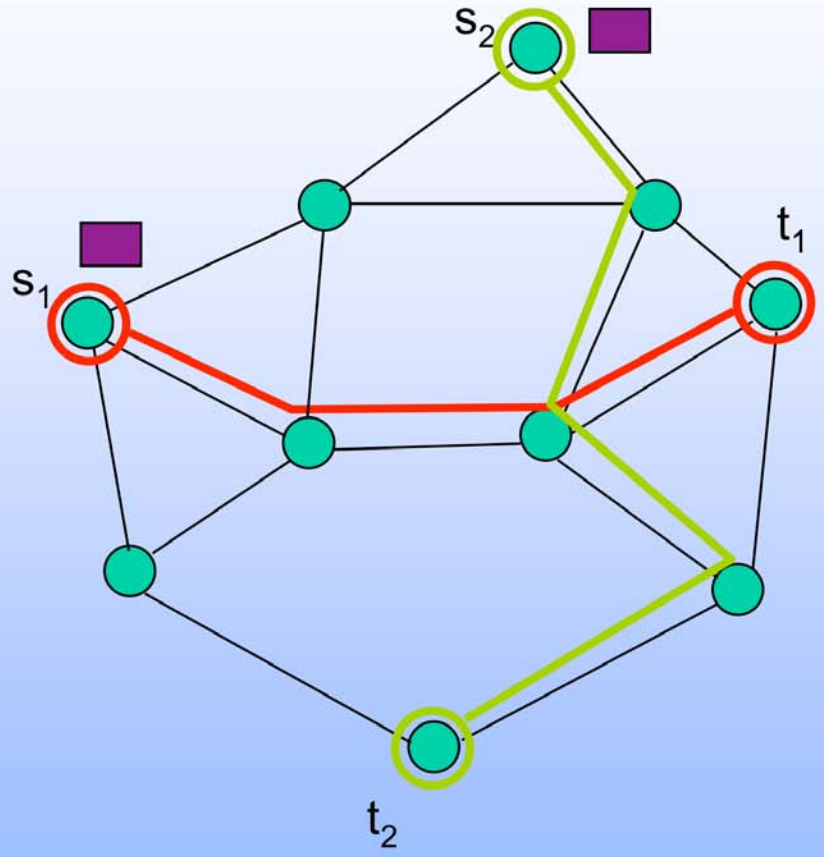
Simultaneous transmission possible on a Distance-2 matching



Instantaneous Capacity: size of largest Distance-2 matching

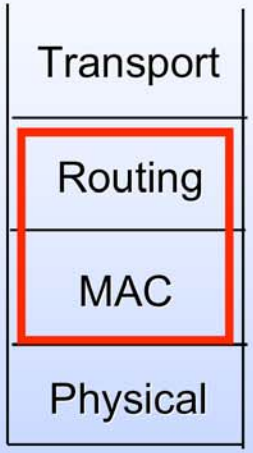
MAC+Routing problem: one D-2 matching at a time

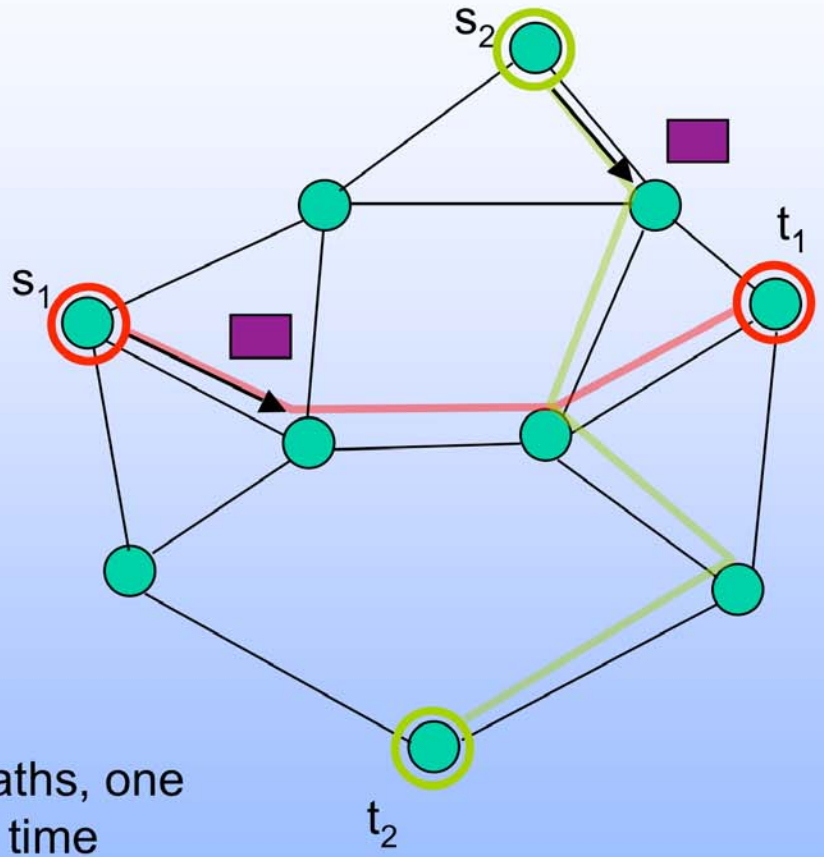




- choose routes

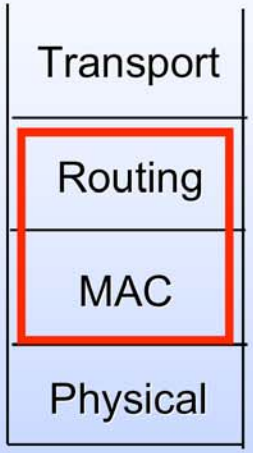
MAC+Routing problem: one D-2 matching at a time

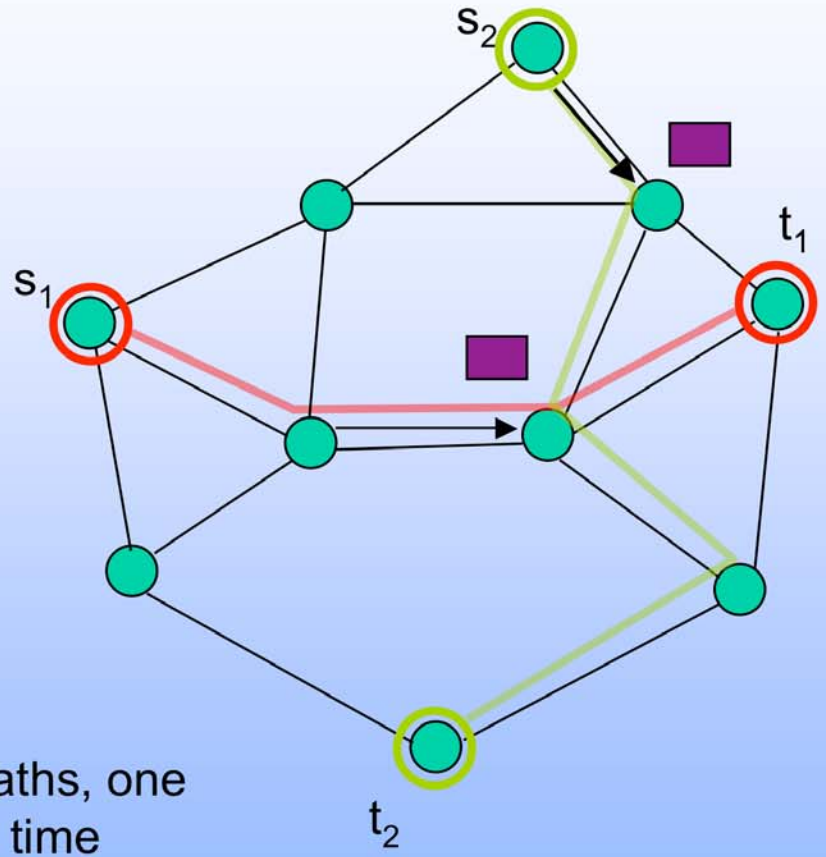




- choose routes
- move along the paths, one D-2 matching at a time

MAC+Routing problem: one D-2 matching at a time





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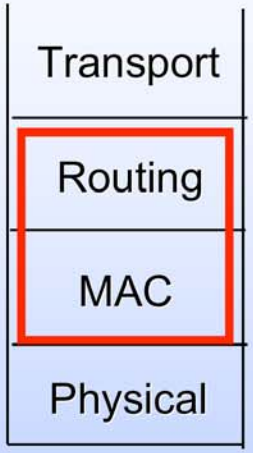

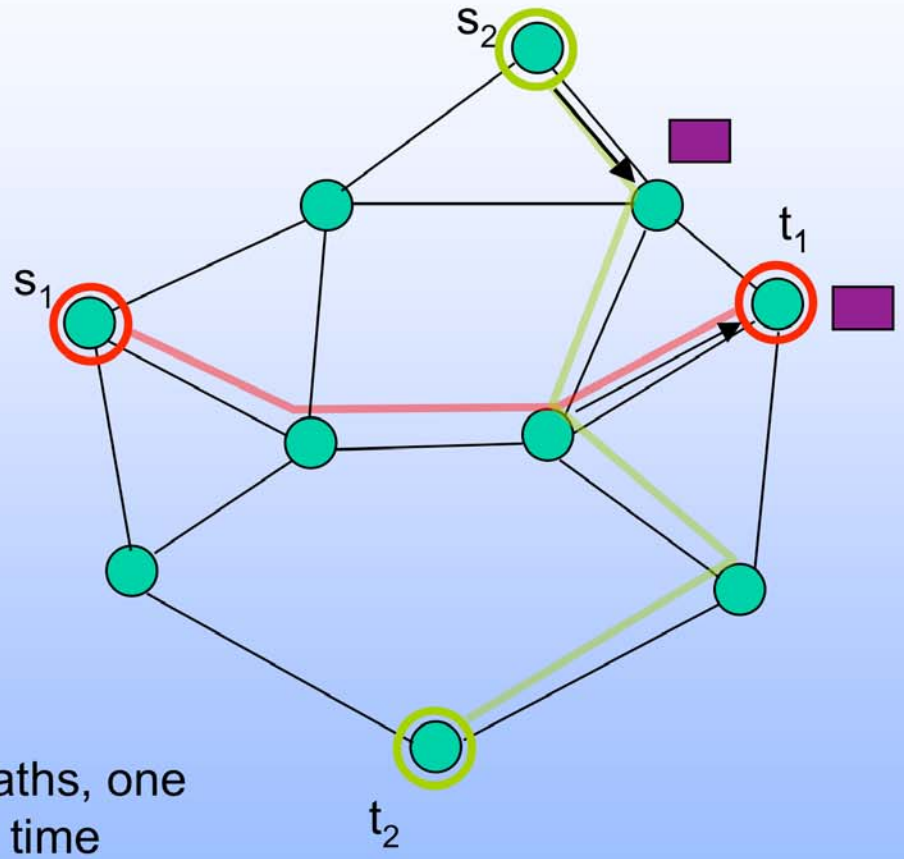

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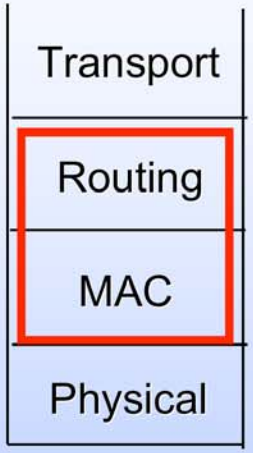

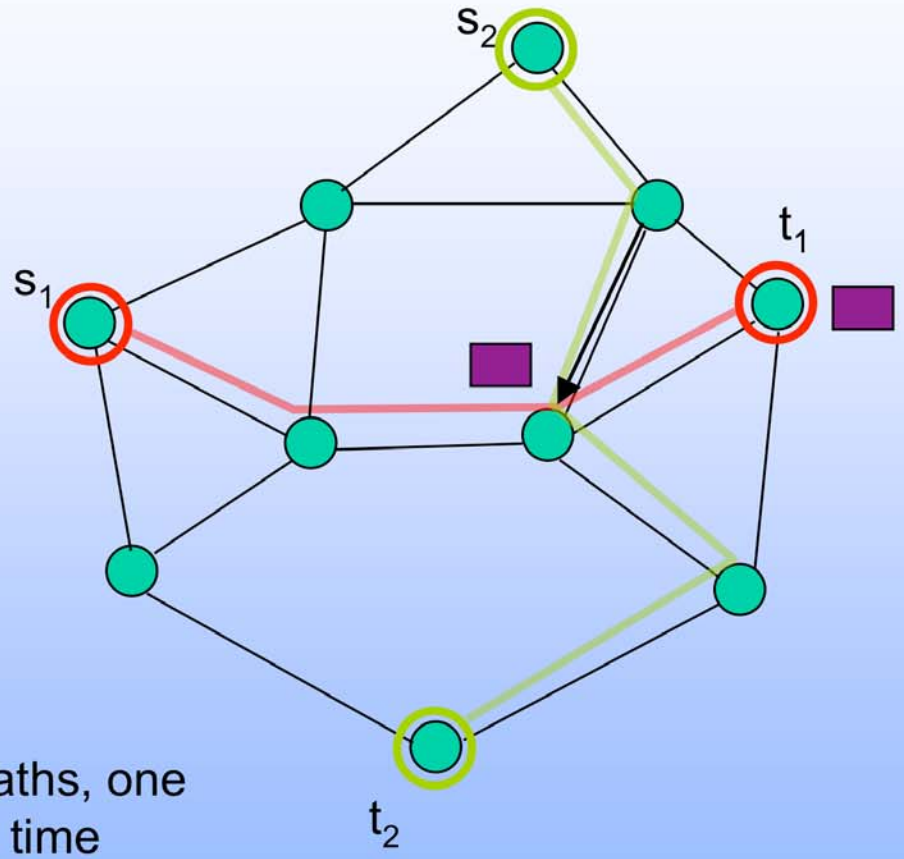

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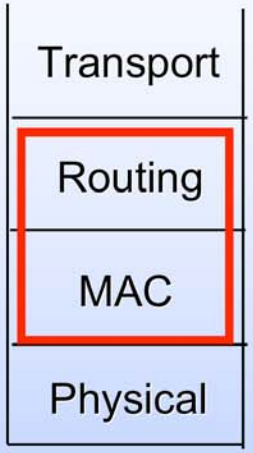

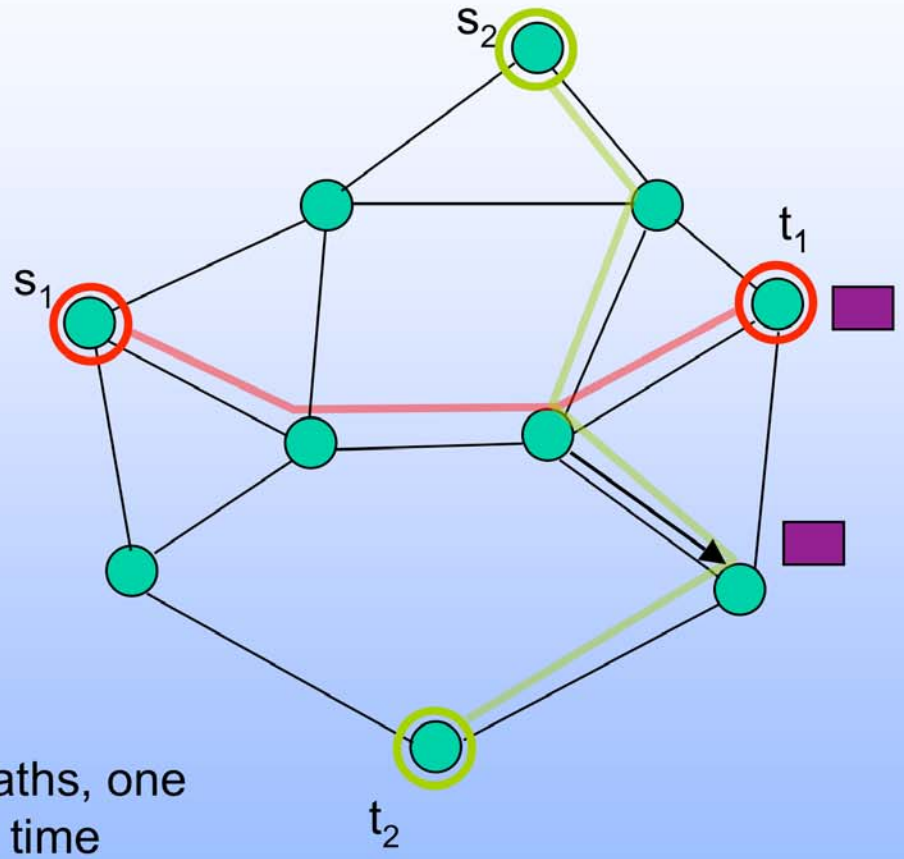

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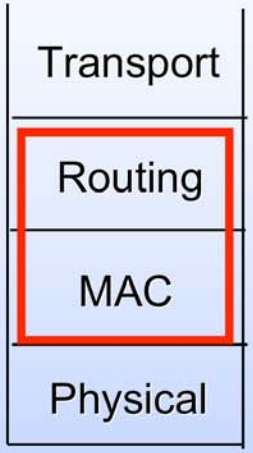
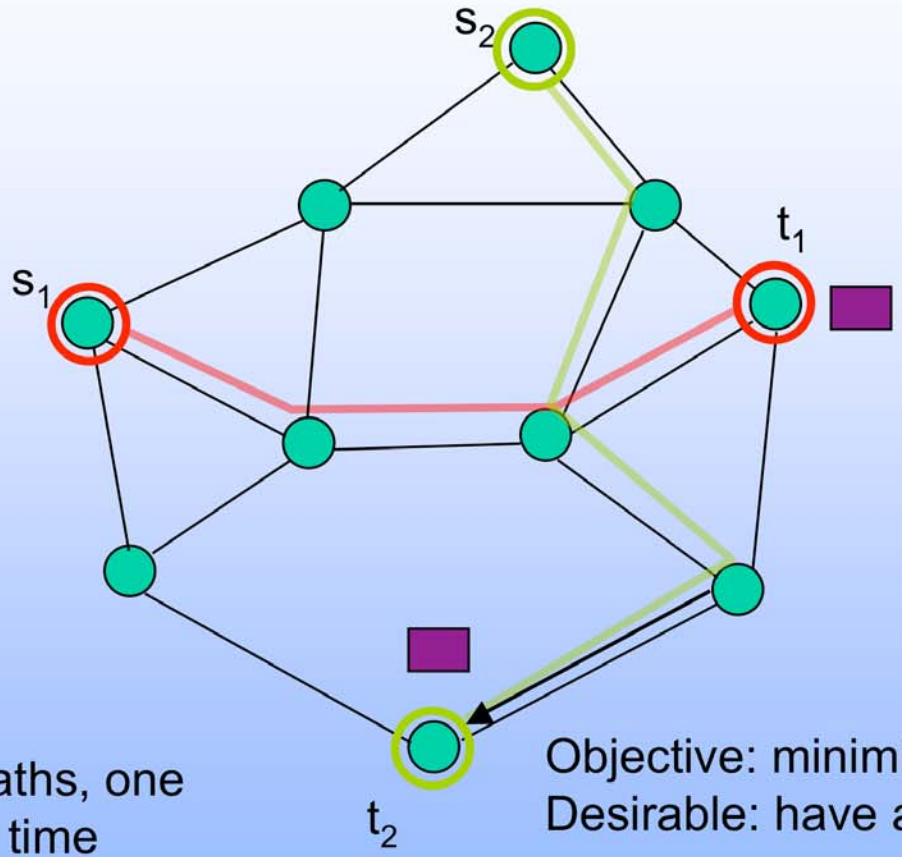
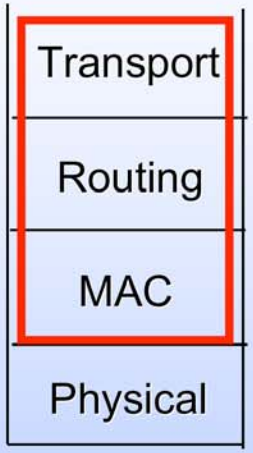


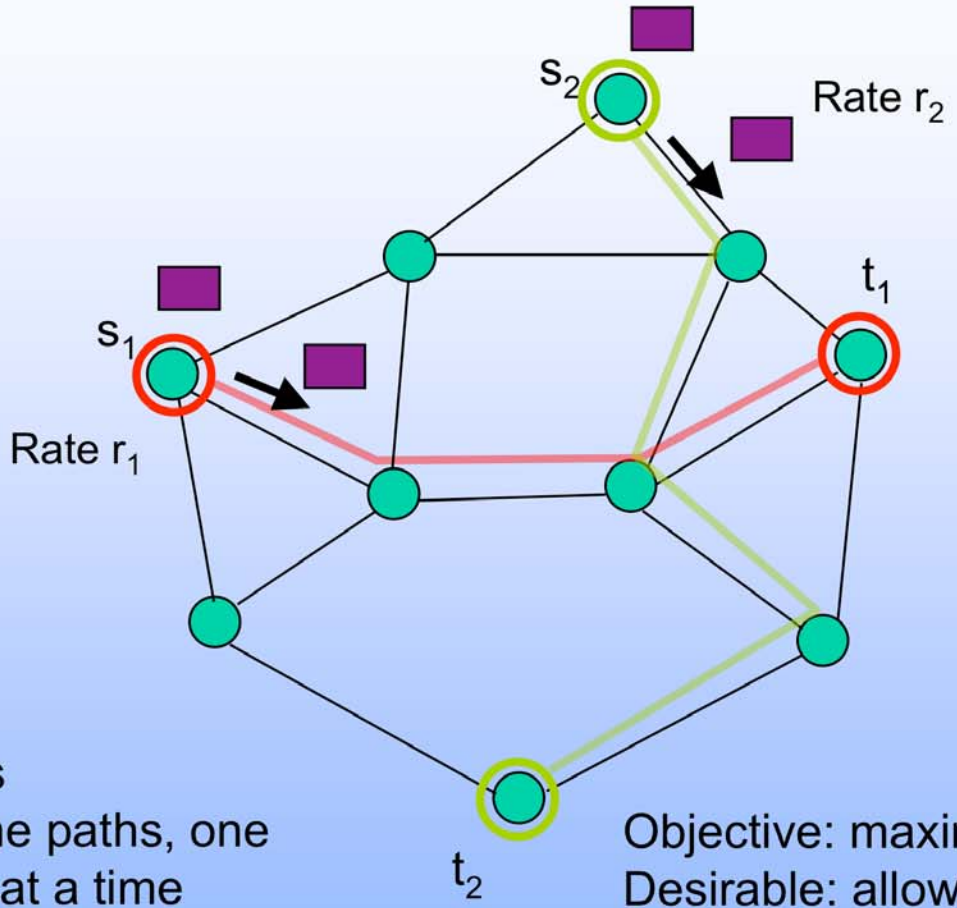


- choose routes
- move along the paths, one D-2 matching at a time

Objective: minimize total time (makespan)
Desirable: have a layered structure

MAC+Routing+Transport problem





- choose routes
- move along the paths, one D-2 matching at a time
- Inject packets at suitable rates

Objective: maximize total throughput
Desirable: allow additional constraints (e.g. fairness)

Summary of Results

- Algorithms for sensor placement

(Maneuvrable Relays to Improve Energy Efficiency in Sensor Networks, S. Eidenbenz, L. Kroc, J.P. Smith, PERCOM 2005)

- Analysis of topology control as non-cooperative games

(Equilibria in Topology control games for ad hoc networks, S. Eidenbenz, V.S. Anil Kumar, S. Zust, DIALM 2003)

- Codes

(A. Hansson and T. Aulin, Generalized APP detection of continuous phase modulation over unknown ISI channels," IEEE Transactions on Communications, accepted, Dec. 2003.
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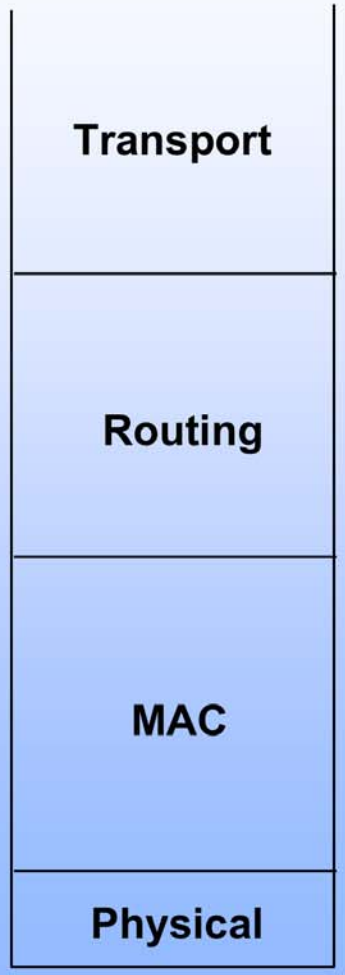

- Very hard *in general*
  - NP-complete
  - no approx better than $\Omega(n^{1-\varepsilon})$
- Disk graphs and other geometric graphs
  - PTAS for instantaneous capacity
  - Distributed O(1) approximation, O(*log n*) rounds
- Empirical improvement in the performance of 802.11

(The distance-2 matching problem and its relationship to the MAC-layer capacity of ad hoc networks, H. Balakrishnan, C. Barrett, V. S. Anil Kumar, M. Marathe, S. Thite, *Special Issue of IEEE Journal on Selected Areas in Communication*)

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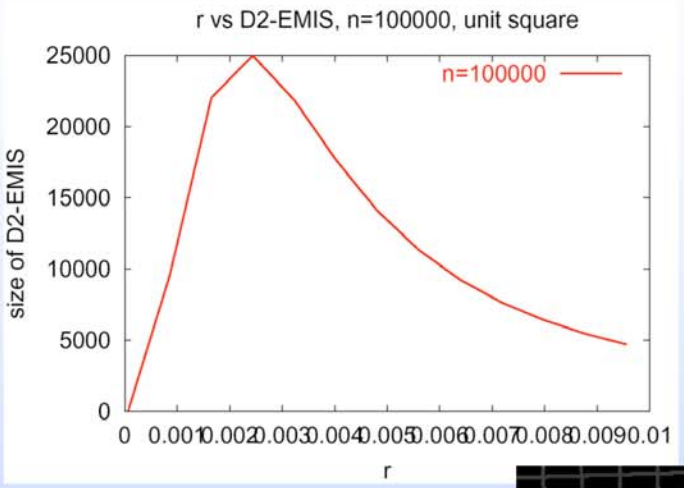
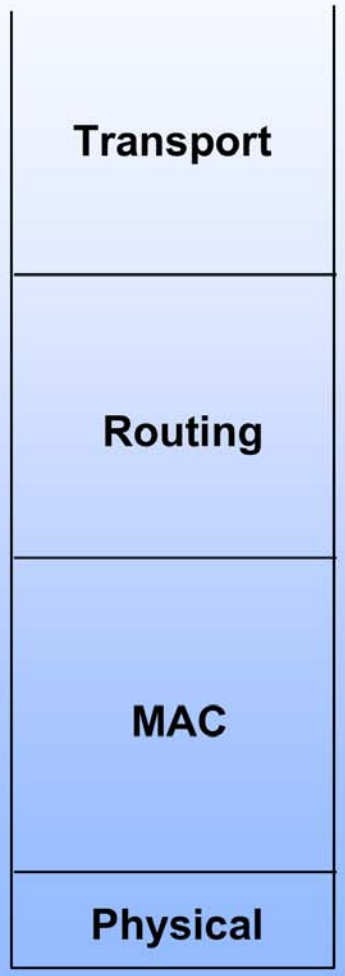


Instantaneous capacity of random points in plane

Maximum ~ $(n/\log n)^{1/2}$ (Gupta-Kumar bound)



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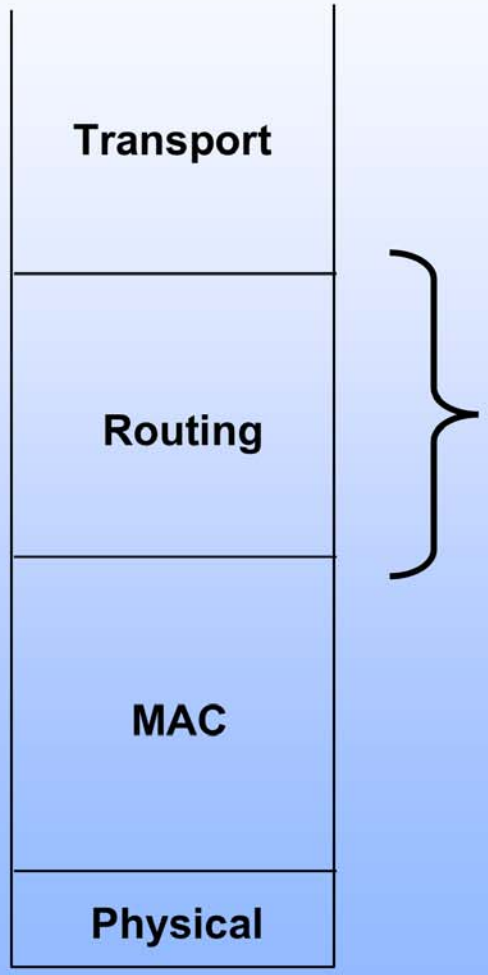
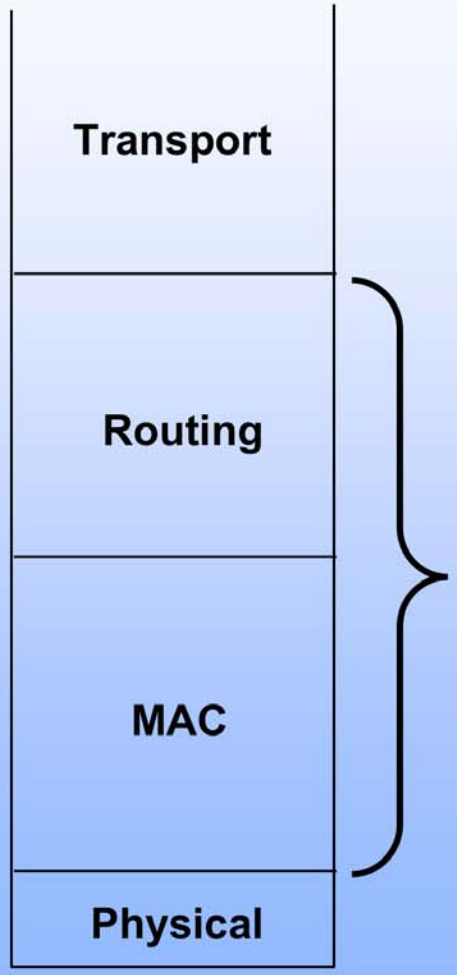


- Parametric Probabilistic Sensor Network Routing
(Parametric Probabilistic Sensor Network Routing, C. Barrett, S. Eidenbenz, L. Kroc, M. Marathe and J. Smith, WSNA 2003)
- Routing with economic incentives
(Ad hoc-VCG: a truthful and cost-efficient routing protocol for mobile ad hoc networks with selfish agents, L. Anderegg and S. Eidenbenz, MOBICOM 2003)
- Locality of information v. search efficiency tradeoffs
(Gabriel Istrate)

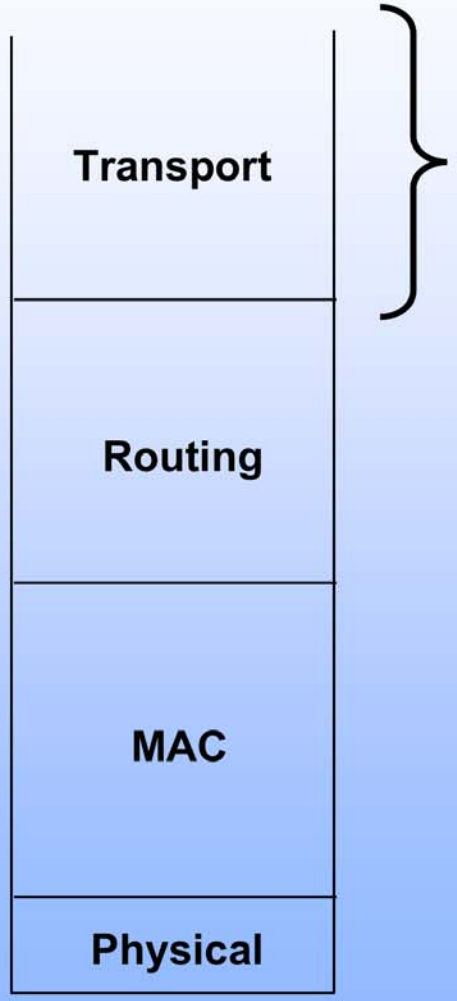
Summary of Results



- New Congestion aware routing protocol
  - Independent Routing and MAC
- Very hard *in general*
  - no approx better than $\Omega(\Delta^{1-\varepsilon})$ possible
  - $O(\Delta \log^2 n)$ approx
- Disk graphs
  - $O(\log^2 n)$ distributed approximation
  - O(1) approx for unit disk, *(r,s)*-civilized graphs and planar graphs

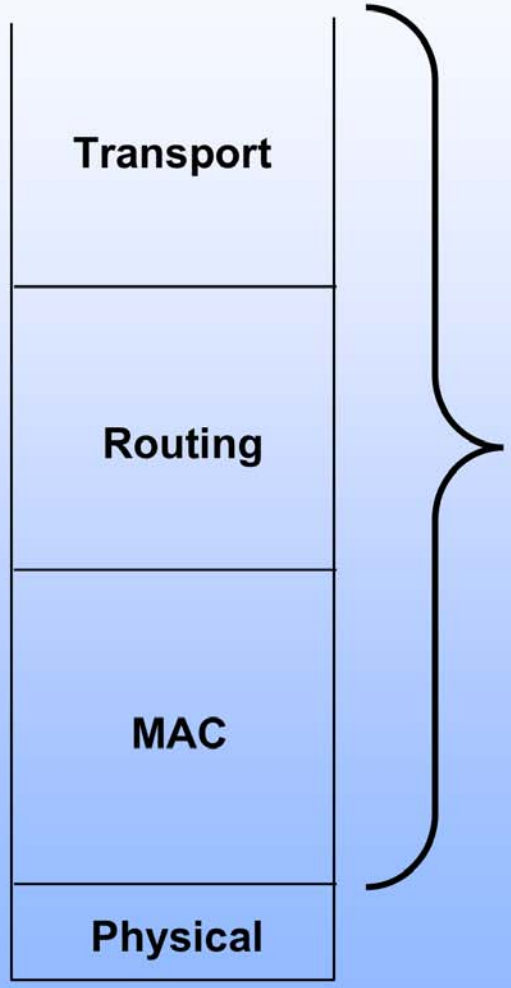
(End-to-end packet scheduling in ad hoc networks, V.S. Anil Kumar, M. Marathe, S. Parthasarathy and A. Srinivasan, *SODA, 2004*)

Summary of Results



- Simpler models for TCP
  (Daria Antinova, Stephan Eidenbenz)
- Dynamics of TCP
  (Gabi Istrate, Anders Hansson: RESTORED in SIGCOM)

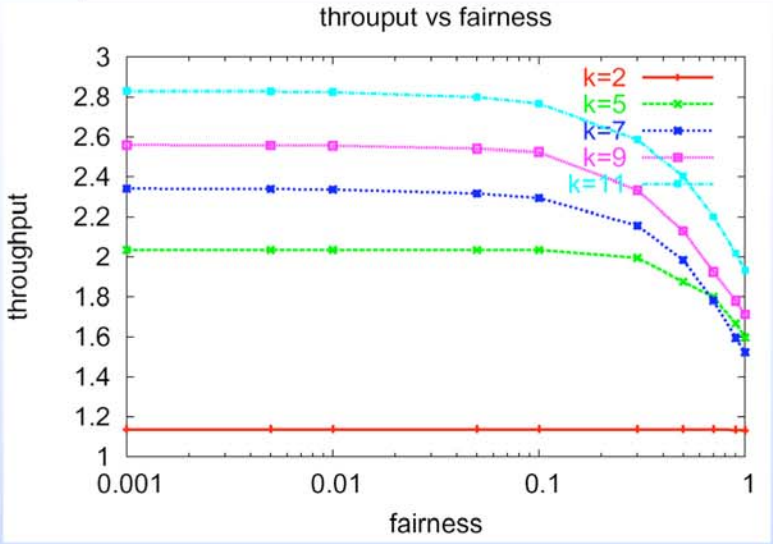
Summary of Results



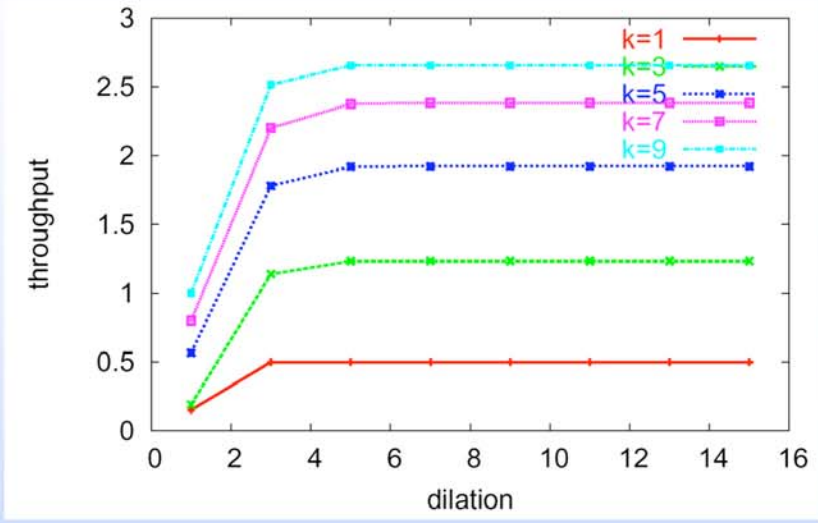
- Algorithmic version of Gupta-Kumar result
- LP framework
- O(1) approximation to total throughput
- New condition for stability
- Improved protocols
- Framework to study the trade-off between any set of linear constraints
  - (long term) fairness vs total throughput
  - energy of paths vs total throughput

(Algorithmic aspects of capacity in wireless networks, V.S. Anil Kumar, M. Marathe, S. Parthasarathy and A. Srinivasan, ACM SIGMETRICS 2005)

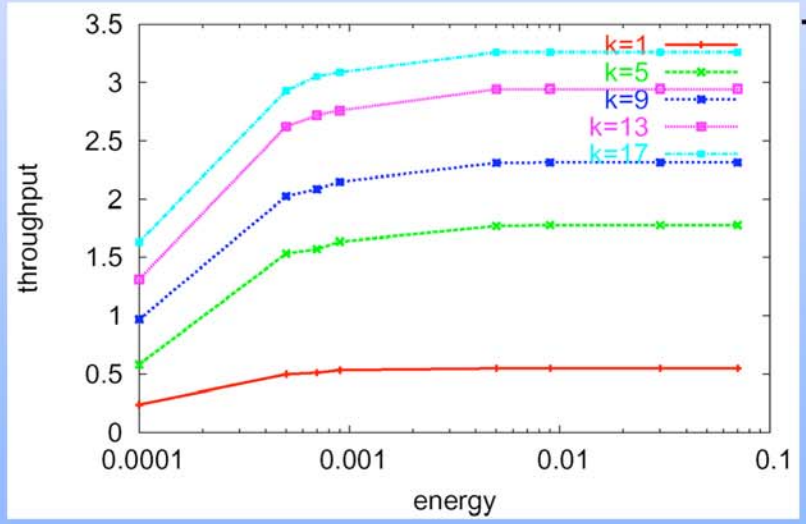
Summary of Results: Effect of different parameters



Throughput vs fairness



Throughput vs path length



Throughput vs energy

Context: Ongoing work

- Goal: Build an end-to-end simulation of very large ($\approx 10^8$ nodes) hybrid 3G+ to 4G networks.
- Approach:
  - Realistic urban population and mobility models
  - Efficient, approximate protocol representation

    (exact implementation will not scale)

  $\Rightarrow$ need for unified protocols
  - Efficient storage, analysis and dynamic regeneration of packet dynamics